

**ELECTRIC FIELD STUDY OF SILICON RUBBER INSULATOR USING
FINITE ELEMENT METHOD (SLIM)**

ROHAIZA BTE HAMDAN

**A project report submitted in partial fulfillments of the
requirements for the award of the degree of
Master of Engineering (Electrical – Power)**

**Faculty of Electrical Engineering
Universiti Teknologi Malaysia**

APRIL 2006

ABSTRACT

Silicone rubber provides an alternative to porcelain and glass regarding to high voltage (HV) insulators and it has been widely used by power utilities since 1980's owing to their superior contaminant performances. Failure of outdoor high voltage (HV) insulator often involves the solid air interface insulation. As result, knowledge of the field distribution around high voltage (HV) insulators is very important to determine the electric field stress occurring on the insulator surface, particularly on the air side of the interface. Thus, concerning to this matter, this project would analyze the electric field distribution of energized silicone rubber high voltage (HV) insulator. For comparative purposes, the analysis is based on two conditions, which are silicon rubber insulators with clean surfaces and silicon rubber insulators with contamination layer taking place over its surfaces. In addition, the effect of water droplets on the insulator surface is also included. The electric field distribution computation is accomplished using SLIM software that performs two dimensions finite element method. The finding from this project shows that pollution layer distort the voltage distribution along the insulator surface while different pollution layer material and variation in zone of incidence would contribute different profile of electric field. Existence of water droplets would create field enhancement at the interface of the water droplet, air and silicon rubber material. Also, the intensification field created by water droplet is depending on the droplets size, number of droplets and the proximity of water droplets to each other.

ABSTRAK

Getah silikon memberikan alternatif kepada porselin serta kaca yang digunakan sebagai penebat voltan tinggi dan ia telah digunakan secara meluas oleh pembekal kuasa semenjak 1980-an memandangkan prestasinya yang baik semasa kehadiran bahan pencemar. Kegagalan penebat voltan tinggi di kawasan terbuka pada kebiasaannya melibatkan bahagian di sempadan penebatan antara udara dan bahan penebat. Sehubungan dengan itu, informasi mengenai penyebaran medan disekitar penebat voltan tinggi adalah amat penting bagi menentukan tekanan medan elektrik yang terbentuk di atas permukaan penebat, terutamanya di bahagian udara pada sempadan antara penebat dan udara. Oleh yang demikian, merujuk kepada perkara tersebut, projek ini akan menganalisa penyebaran medan elektrik bagi penebat getah silikon voltan tinggi. Bagi tujuan perbandingan, analisa yang dilakukan adalah berdasarkan kepada dua situasi, getah silikon yang mempunyai permukaan yang bersih dan getah silikon yang mempunyai lapisan bahan pencemar di sepanjang bahagian permukaannya. Selain daripada itu, kesan titisan air yang terdapat di atas permukaan penebat juga dirangkumkan. Pengiraan bagi sebaran medan elektrik pada permukaan penebat disempurnakan menggunakan perisian SLIM yang melaksanakan kaedah elemen tak terhingga dua dimensi. Hasil daripada projek ini menunjukkan bahawa kehadiran lapisan pencemar memesongkan pengagihan voltan di sepanjang permukaan penebat sementara bahan pencemar yang berbeza serta variasi kepada zon yang terlibat akan menyumbang kepada profil medan elektrik yang berbeza. Kehadiran titisan air akan menghasilkan pertambahan medan di sempadan antara air, udara dan bahan getah silikon. Disamping itu, pertambahan tekanan medan yang dibentuk oleh titisan air adalah bergantung kepada saiz titisan, bilangan titisan dan jarak di antara satu titisan dengan titisan yang lain.

TABLE OF CONTENT

CHAPTER	TITLE	PAGE
	DECLARATION	ii
	DEDICATION	iii
	ACKNOWLEDGEMENT	iv
	ABSTRACT	v
	ABSTRAK	vi
	TABLE OF CONTENTS	vii
	LIST OF FIGURES	xii
	LIST OF TABLES	xiv
	LIST OF SYMBOLS / ABBREVIATIONS	xv
	LIST OF APPENDICES	xvi
I	INTRODUCTION	1
	1.0 Introduction	1
	1.1 The Objective of the Project	1
	1.2 The Scope of the Project	2
	1.3 The Project Schedule	2
	1.4 Thesis Outline	3
2	FINITE ELEMENT METHOD	4

2.0	Introduction	4
2.1	Historical Background of Finite Element Method	5
2.2	Finite Element Method (FEM) Application in Electrical Engineering	7
2.3	Definition of Finite Element Methods (FEM)	9
2.4	Steps Included in Finite Element Method (FEM)	11
2.4.1	Pre-processing: Defining the Finite Element Model	11
2.4.2	Solution: Solving for Displacement, Stress, Strain etc	12
2.4.3	Post-processing: Reviewing Results in Text and Graphical Form	12
2.5	Domain Discretization	13
2.5.1	Types of Elements	15
2.5.2	Continuous Mesh	16
2.5.3	The Quality of Mesh	18
2.5.4	Node Numbering	19
2.5.5	Element Interpolation	20
2.6	Element Governing Equation	21
2.6.1	Element Coefficient Matrix	23
2.7	Assembling of All Elements	23
2.8	Solving the Resulting Equation	25
2.9	Source of Error in Finite Element Method (FEM)	25
2.10	Advantages of Finite Element Method (FEM)	27
2.11	Disadvantages of Finite Element Method (FEM)	28
3	SILICONE RUBBER INSULATOR	29
3.0	Introduction	29
3.1	Historical Background of Silicon Rubber	29
3.2	Properties of Silicon Rubber	33
3.2.1	Advantages of Silicon Rubber	35

3.3	Hydrophobicity of Silicon Rubber	35
3.4	Pollution Flashover Mechanism of Silicon Rubber	37
3.5	Contamination Build Up	38
3.5.1	Sea Pollution	39
3.5.2	Inland Pollution	39
3.6	Diffusion of Low Molecular Weight Chains	40
3.7	Wetting of the Surface	40
3.7.1	Migration of the Pollutant to the Droplets	41
3.7.2	Migration of the Water into the Dry Pollutant	41
3.8	Ohmic Heating	42
3.9	Effect of Electric Field on Water Droplet	42
3.10	Spot Discharge	43
3.11	Loss of Hydrophobicity	44
3.11.1	Elongation of Filaments	44
3.11.2	Formation of Wet Region	44
3.12	Flashover	45
4	RESEARCH METHODOLOGY	46
4.0	Introduction	46
4.1	Procedure Involved	46
4.1.1	Gathering Information.	47
4.1.2	Simulation Implementation	47
4.1.3	Results Analysis	47
4.2	Research Sample	48
4.3	Instrumental Requirement	48
4.4	Software Utilization	48
4.4.1	Mesh Generation Modules	49
4.4.2	Data Preparation Modules	49
4.4.3	Field Solution Modules	50
4.4.4	Post Processing Modules	51
4.5	Simulation Model	52

4.5.1	Clean Model of Silicon Rubber	52
4.5.2	Contaminated Model of Silicon Rubber	55
4.5.3	Water Effect Model	57
5	RESULTS AND DISCUSSIONS	59
5.0	Introduction	59
5.1	Simulation Results for Clean Insulator	59
5.1.1	Parameters Variation Effect on Electric Fields of a Clean Insulator	62
5.1.1.1	Effect of Varying Slope Angle	62
5.1.1.2	Effect of Varying Shed Radius	63
5.1.1.3	Effect of Varying Core Radius	64
5.1.1.4	Effect of Axial Height	65
5.1.1.5	Effect of Inner Corner Radius	66
5.1.1.6	Effect of Outer Corner Radius	66
5.2	Simulation Results for Contaminated Insulator	67
5.2.1	Effect of Uniform Pollution Layer	68
5.2.2	Effect of Contamination Materials	70
5.2.3	Effect of the Zone of Partial Surface Pollution	71
5.3	Simulation Results for Water Droplets Effect	72
5.3.1	Effect of a Single Water Droplet on Electric Field	73
5.3.2	Effect of Multiple Water Droplets on Electric Field	76
5.3.3	Effect of Distance between Water Droplets on Electric Field	79
5.3.4	Effect of Size of Water Droplets on Electric Field	79
5.4	Conclusion	82

6	FUTURE WORKS RECOMMENDATIONS	83
6.0	Introduction	83
6.1	Further Recommendations	83
	REFERENCES	85
	APPENDICES	89

LIST OF FIGURES

FIGURE	TITLE	PAGE
2.1	Typical finite element subdivisions of an irregular domain and typical triangular element.	9
2.2	Deformation of two elements with nodal compatibility.	14
2.3	Deformation of two elements with Finite element Method (FEM).	14
2.4	A variety of solid and shell finite elements.	15
2.5	A rectangular region with the number of elements on the boundaries.	16
2.6	A discontinuous meshing within the rectangular region	17
2.7	Examples of continuous meshing of a rectangular region.	17
2.8	Mesh distortion of an element.	19
2.9	Linear triangular element.	22
2.10	Assembling of all elements.	24
2.11	Discretization errors due to poor geometry representation.	25
2.12	Discretization error effectively eliminated.	26
2.13	Sample of the formulation error.	26
3.1	Molecular chain of polydimethylsiloxane (PDMS)	33
3.2	Intrinsic hydrophobic property of unpolluted high temperature vulcanizes (HTV) silicon rubber surfaces.	37
3.3	Hydrophobicity transfer to pollution layers on silicon rubber surface covered with thick and heavy artificial pollution in form of a kaolin slurry.	39
3.4	Hydrophobicity transfer to pollution layers on silicon	

	rubber surface covered with natural pollution layer after 21 years in service.	40
3.5	Migration of the pollutant to the droplets.	41
3.6	Migration of the water into the dry pollutant.	42
3.7	Effect of electric field on water droplet.	43
3.8	Spot discharge formation.	43
3.9	The formation of wet region.	45
3.10	Flashover on the insulator surface.	45
4.1	Simulation input and output flow.	52
4.2	Small models for silicon rubber insulator (scale in mm).	53
4.3	Shed numbering.	56
4.4	Set up for analyzing effect of a water droplet on silicon rubber surface.	57
5.1	Mesh generated for clean insulator.	60
5.2	Voltage contour of a clean insulator.	61
5.3	Voltage distribution of a clean insulator.	61
5.4	Electric field distribution of a clean insulator.	62
5.5	Mesh generated for a uniformly polluted insulator.	68
5.6	Voltage contour of a uniformly polluted insulator.	69
5.7	Voltage distribution of a uniformly polluted insulator.	69
5.8	Electric field distribution of a uniformly polluted insulator.	70
5.9	Equipotential line generated from model with one water droplet.	73
5.10	Enlargement of equipotential line generated for one droplet of water.	74
5.11	Electric field stress around one droplet of water on silicon rubber surface.	74
5.12	Voltage distributions profile on effect of one water droplet.	75
5.13	Field distribution profile on effect of one water droplets.	77
5.14	Field distribution profile on effect of multiple water droplets.	78
5.15	Field distribution profile on effect of distance between water droplets.	80
5.16	Field distribution profile on effect of size of water droplets.	81

LIST OF TABLES

TABLE	TITLE	PAGE
3.1	First generation commercial polymeric transmission line insulator.	32
4.1	Parameter for clean model insulator	54
4.2	Contamination layer materials	55
5.1	Effect of the insulator slope angle on the maximum field stress at the surface of clean insulator.	63
5.1	Effect of the insulator slope angle on the maximum field stress at the surface of clean insulator.	64
5.3	Effect of the insulator core radius on the maximum field stress at the surface of clean insulator.	65
5.4	Effect of the insulator axial height on the maximum field stress at the surface of clean insulator.	66
5.5	Effect of the insulator inner corner radius on the maximum field stress at the surface of clean insulator.	67
5.6	Effect of the insulator outer corner radius on the maximum field stress at the surface of clean insulator.	67
5.7	Comparison on the maximum field stress of the insulator surfaces with various types of pollutant.	71
5.8	Effect of the partial surface pollution on the maximum field stress of the silicon rubber surface.	72

LIST OF SYMBOLS / ABBREVIATIONS

D	-Distortion factor.
H	-Size of the element.
R	-Diameter of the largest circle in the element.
V	-Volt
m	-Meter
h_i	-Axial height
r_e	-Electrode radius
r_{ec}	-Electrode corner radius
r_i	-Core radius
r_{ic}	-Inner corner radius (the radius of curve fitting between shed and sheath)
r_o	-Shed radius
r_{oc}	-Outer corner radius (the radius of curve fitting between the upper and bottom shed)
E_{max}	-Maximum field at the surface
θ	-Shed slope angle (the slope angle of the upper shed)
ε	-Permittivity
$^{\circ}$	-Degree

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	Work schedules for Project I.	89
B	Work schedules for Project II.	90
C	Example of the control file	91

CHAPTER 1

INTRODUCTION

1.0 Introduction

This chapter would describe the overall overview of the project which includes the project objective, scope, project schedule and the outline of the thesis.

1.1 The Objective of the Project

The main objective of this project is to carry out a study on the electric field distribution of energized silicon rubber insulator under clean and contaminated condition using finite element method which is simulated by SLIM software.

1.2 The Scope of the Project

In order to limit this project under certain degree, the objectives of this project are assisted by certain scopes. Those scopes are as listed below:

- a) To appreciate the application of two dimensional linear finite element numerical method in electric field calculation.
- b) To observe and investigate the properties of silicon rubber.
- c) To implement the finite element method technique using SLIM.
- d) To model the contamination layer on the surface of silicon rubber insulator.
- e) To study the electric field pattern of silicon rubber insulator under clean and contaminated condition of energized silicon rubber insulator.

1.3 The Project Schedule

This project was accomplished in two consecutive phases which are Project I and Project II where Project II is the continuation from Project I. The theoretical part is being covered mostly within the Project I timeframe while Project II depict the simulation analysis of the project. Those project schedules are given separately by Appendix A.

1.4 Thesis Outline

This thesis is being divided into six consecutive chapters where each chapter review different issues regarding to the project objectives. Chapter 1 covers the introductory section of the project while Chapter 2 and Chapter 3 described the literature review and theoretical background that related to finite element method and silicon rubber respectively. The following chapter is Chapter 4 where this chapter provides the explanation on project methodology used throughout the operation of the project. Simulation results and analysis is explained individually in Chapter 5 and the last chapter, which is Chapter 6, considers the future recommendations in extending the project into a better prospect.

REFERENCES

1. P. Silvester and M.V.K. Chari, "Finite Element Solution of Saturable Magnetic Field Problems," IEEE Trans. PAS-89,, No. 7, pp. i642-i65i, 1970.
2. P. Silvester, H.S. Cabayan and B.T. Browne, IEEE Trans. PAS-92. No. 4. 1973.
3. O.W. Andersen, "Transformer Leakage Flux Program Based on the Finite Element Method," IEEE Trans. PAS-92, No. 2, 1973,
4. M.V.K. Chari and P. Silvester, "Analysis of Turbo-Alternator Magnetic Fields by Finite Elements," IEEE Trans. PAS-90, pp. 454- 464, 1971.
5. M.V.K. Chari, "Finite Element Solution of the Eddy Current Problem in Magnetic Structures," IEEE Trans. PAS-92, Vol. 1, 1973.
6. A.Y. Hannalla and D.C. MacDonald, "Numerical Analysis of Transient Field Problems in Electrical Machines," Proc. IEE, Vol.
7. J.L. Coulomb, "A Methodology for the Determination of Global Electromechanical Quantities from a Finite Element Analysis and Its Application to the Evaluation of Magnetic Forces, Torques and Stiffness," IEEE Trans. MAG-19, 5, pp. 2514-2519, 1983.
8. J. D'Angelo and I.D. Mayergoyz, "Three Dimensional RF Scattering by the Finite Element Method," IEEE Trans. on Magnetics

9. M.V.K. Chari and G. Bedrosian, "Hybrid Harmonic Finite Element Method for Two-Dimensional Open Boundary Problems," IEEE Trans. Magnetics, Vol. 23, No. 5, pp. 3572-3, 1987.
10. M.V.K. Chari, J. D'Angelo, M.A. Palmo and A. Konrad, "Three-Dimensional Vector Potential Analysis for Machine Field Problems," IEEE Trans. on Magnetics, Compumag Conference, Vol. 27, No. 5, pp. 3827-3832, 1991.
11. M.V.K. Chari, G. Bedrosian, J. D'Angelo and A. Konrad, "Finite Element Applications in Electrical Engineering", IEEE Trans. on Magnetics, Vol. 29, NO. 2, pp 1306 – 1315, 1993
12. Sri Sundhar, Al Bernstof, Waymon Goch, Don Linston, and Lisa Huntsman, "Polymer Insulating Material and Insulators for High Voltage Outdoor Application", Conference of the IEEE Symposium on Electrical Insulation, June 7-10 1992, Baltimore, pp 222-228.
13. James F. Hall, "History and Bibliography of Polymeric Insulators for Outdoor Applications", IEEE Trans. On Power Delivery, Vol. 8, No. 1, pp. 376-385, 1993.
14. R. Allen Bernstof, Randall K Niedermier and David S Winkler, *Polymer compound Used in High Voltage Insulators*, Hubbel Power System, The Ohio Brass Company.
15. Kim J, Chaudury M K and Owen M J, "Hydrophobicity Loss and Recovery of Silicone HV Insulation", IEEE Trans Dielectrics EI, Vol 6, No 5, pp 695-702, 1999.
16. Krivda A, Hunt SM, Cash G A and George G A, "Characterisation of LMW PDMS in High Voltage HTVSilicone Rubber Insulators", IEEE CEIDP, Victoria BC Canada, pp 703-708, 2000.

17. K Elridge, J Xu, W Yin, A M Jeffry, J Ronzello and S A Bogs, "Degradation of a Silicon Based Coating in Substation Application", IEEE Trans Power Delivery, Vol 14, No 1, pp 188-193, 1999.
18. H Hommma, T Kuroyagi, K izumi, C L Mirley, J Ronzello and S A Boggs, "Evaluation of Surface Degradation of Silicone Rubber Using Gas Chromatography/Mass Spectroscopy", IEEE Trans Power Delivery, Vol 115, pp 796-803, 2000.
19. S Kumagai, N Yoshimura, "Tracking and Erosion of HTV Silicone Rubber and Supression Mechanism of ATH", IEEE Trans Dielectric EI, Vol 8, No 2, pp 203-211, 2001.
20. T G Gustavsson, H Hilborg, S M Gubanski, S Karlsson and U W Gedde, "Aging of Sillicone Rubber Materials Under AC and Dc Voltages in a Coastal Environment", IEEE Trans Dielectric EI, Vol 8, pp 1029-1039, 2001.
21. Wang Shaowu, Liang Xidong and Huang Lendceng, "Experimental Study on the Pollution Flashover Mechanism of Polymer Insulators", IEEE, pp2830-833, 2000.
22. R S Gorur, J Chang and O G Amburgey, " Surface hydrophobicity of polymers used for Outdoor Insulation", IEEE Trans on Power Delivery, Vol 5, No 4, pp 1923-1933, 1990
23. R S Gorur, G G Karady, A Jagota, M Shah and A M Yates, " Aging in Silicon Rubber Used for Outdoor Insulation", IEEE Trans on Power Delivery, Vol 7, No 2, pp 525-538, 1992.
24. Chen Yuan, Guan Zhicheng and Liang Xidong, "Analysis of Flashover on the Contaminated Silicon Rubber Composite Insulator", Proceeding of the 5th international Conference on PADM, May 25-30, Seoul, Korea, pp 914-917, 1997.

25. S E Schwarz, “ SLIM;A Slender Technique for Unbounded Field Problem’, IEEE Microwave Theory and Technique, vol 46, no 7, July 1998, pp 1022-1024.
26. S. S. Rao, (1989), *The Finite Element Method In Engineering*, 2nd Eds, Pergamon Press, England.
27. A. J. Baker and D. W. Pepper, (1991), *Finite Elements 1-2-3*, 1st Ed, Mc Graw Hill, United State of America.
28. M. S. Naidu and V. Kamaraju, (2000), *High Voltage Engineering*, 2nd Eds, Mc Graw Hill Publishing Company Limited, New Delhi.
29. James T. Boyle, David K. Brown, Bill Mair, Phiroze Mehta and Jim Wood, (1993), *Finite Element Analysis*, 1st Ed, Elsevier Science, England.